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Title: Global to Coastal Multiscale Modeling via Land-river-ocean Coupling in the Energy Exascale Earth System Model (E3SM)

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Global to Coastal Multiscale Modeling via Land-river-ocean Coupling in the Energy Exascale Earth System Model (E3SM)

Phillip J. Wolfram, Steven Brus, Mark Petersen, Zhendong Cao, Darren Engwirda, Xylar Asay-Davis, Mathew Maltrud, Jon Wolfe, Andrew Roberts, Tian Zhou, Gautam Bisht, Zeli Tan, Ruby Leung

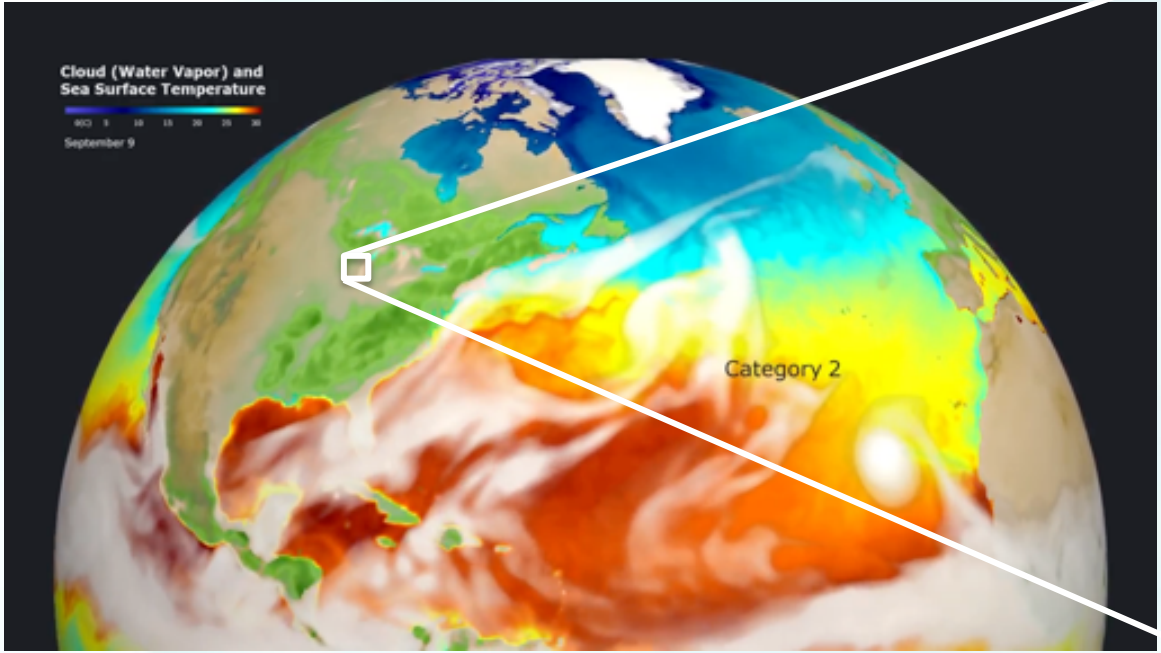
June 11, 2020

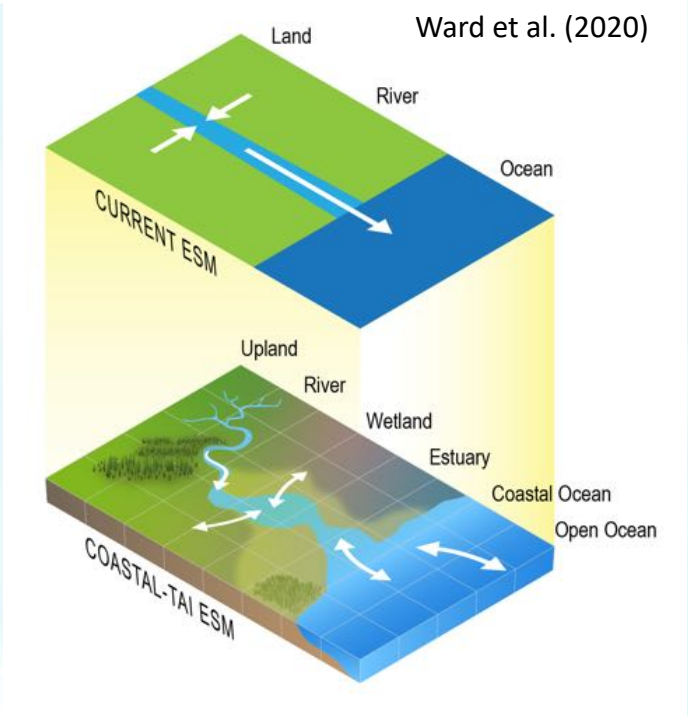
ESCO 2020

E3SM Energy Exascale Earth System Model

U.S. DEPARTMENT OF ENERGY

Energy Exascale Earth System Model (E3SM) v1 High-resolution Water Cycle results

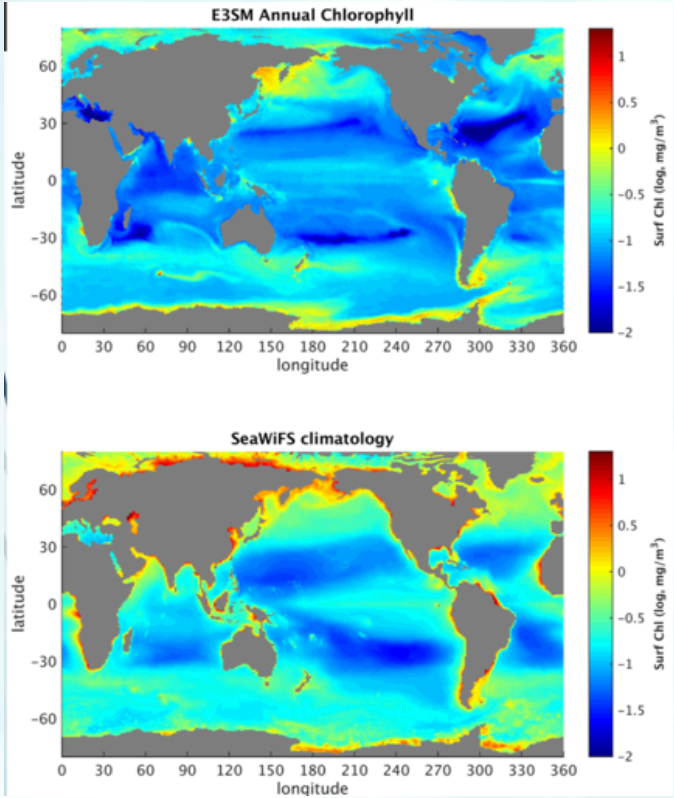




E3SM high-resolution coupled water cycle experiments

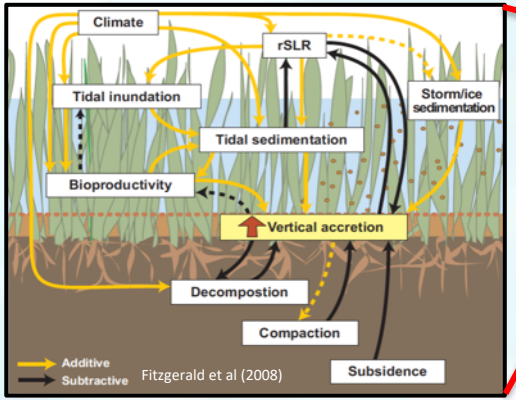
Why Coastal Earth System Modeling? (Mathew Maltrud et al)

- **Global Chlorophyll comparisons**
- Annual mean chlorophyll (mg/m^3) E3SM (yrs 25 -30) and Satellite climatology show similar patterns at large scales (but magnitudes different)
  - **Too little coastal production**
  - **Resolution too coarse to represent coastal zone**
- Multiscale simulation requires tuning

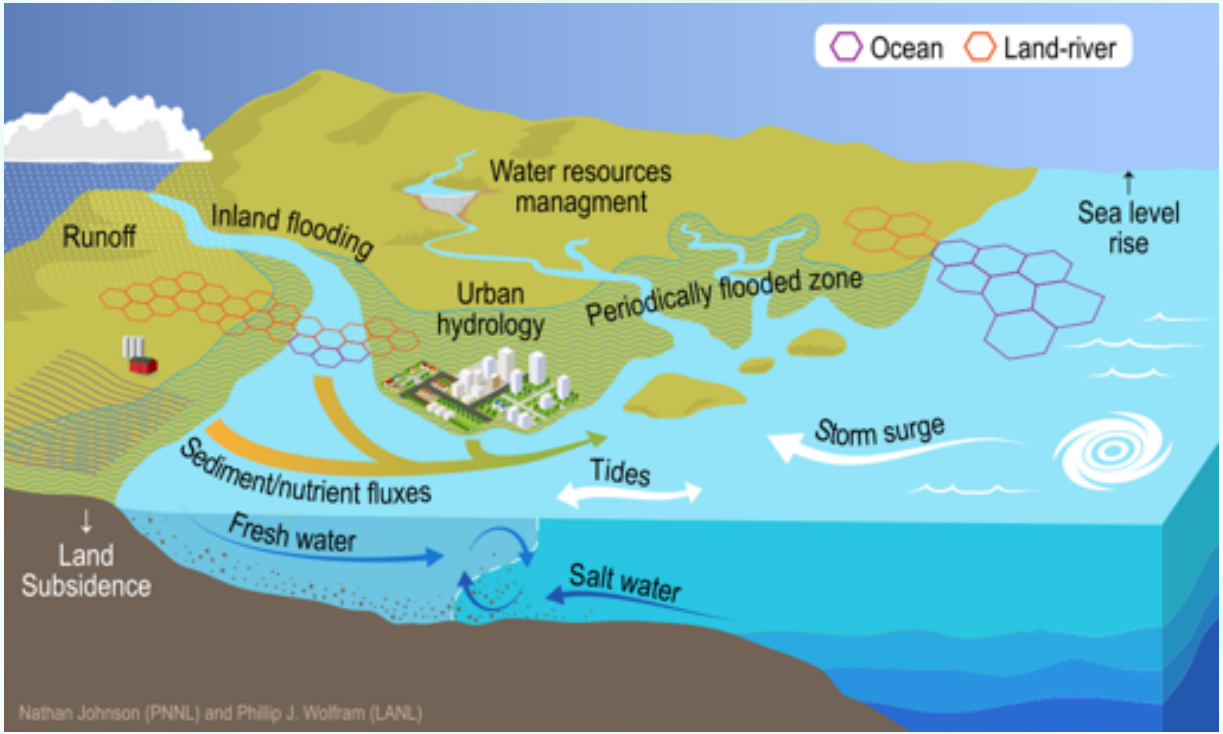


Coastal System Evolution of the Land-River-Ocean Coastal Interface

- Human system modifies coastal drivers
- Natural system evolution can be drastic (e.g., strong fluid flows/sediment transport)
- Coastal biogeochemistry mediated by short and long term land-river-ocean flows/fluxes
- Large to small scale processes dependence



Strong coastal impacts and evolution at coast

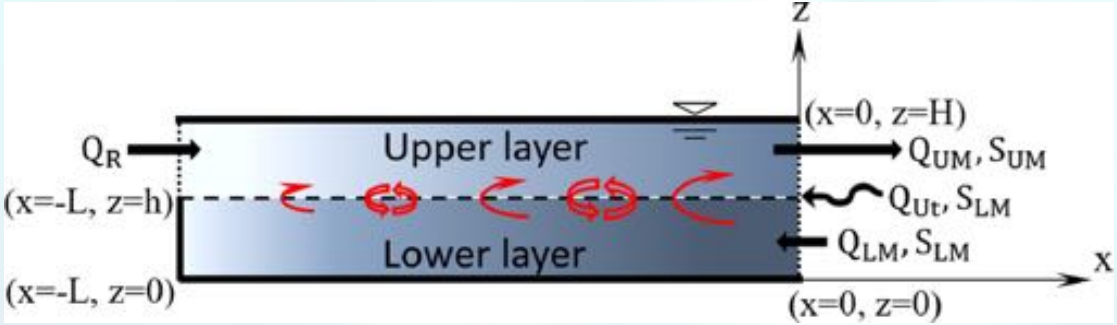


Fresh-salt water flow balance

Sediment and nutrient fluxes

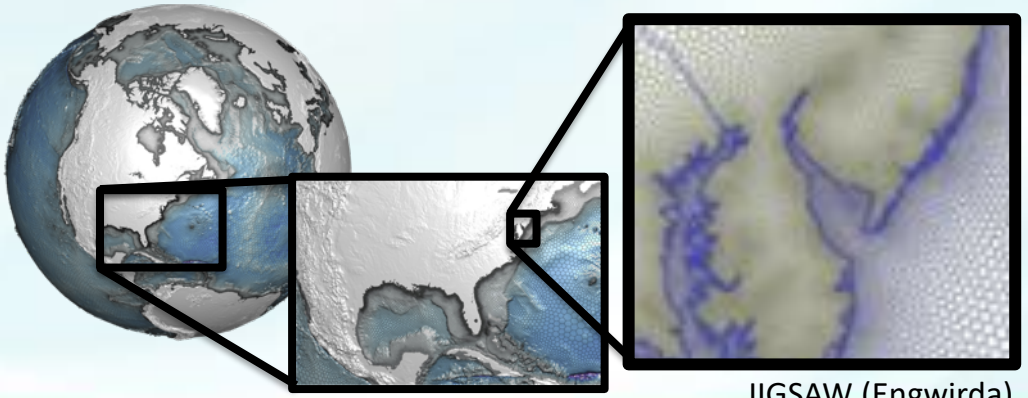
Coastal System Evolution in an E3SM

- Previous simplified coastal climate modeling (no/limited feedback)
  - Box models (e.g., CESM)
  - Nesting (e.g., ROMS)
  - Offline simulation (e.g., IPCC)



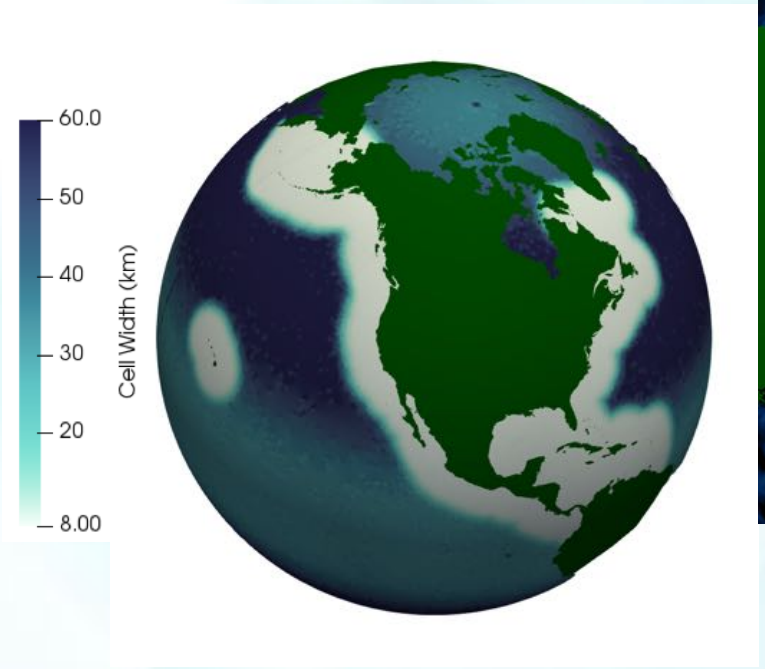
Box model (Sun et al 2017)

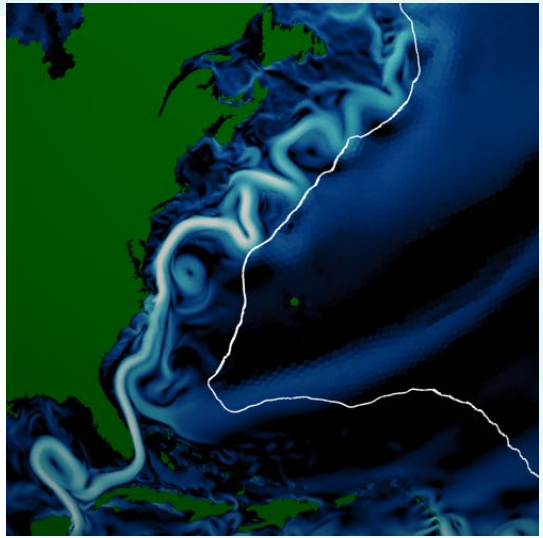
- We are developing a new seamless global to coastal climate modeling capability in E3SM

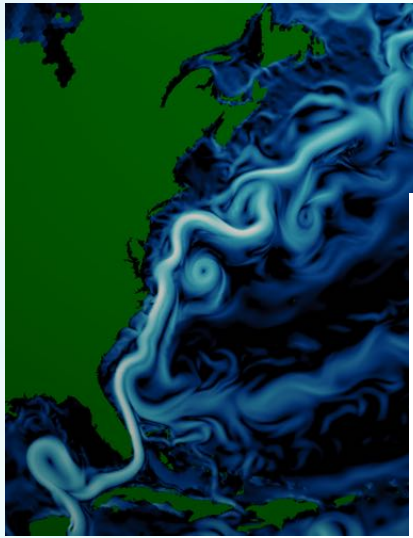


JIGSAW (Engwirda)

Coastal modeling using multiresolution (Hoch et al, 2020)







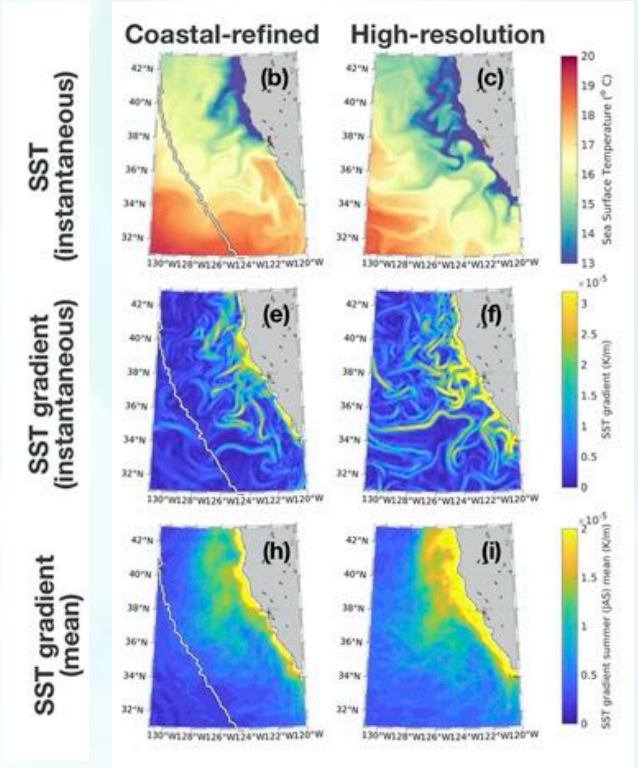
8km coastal refinement

High-resolution

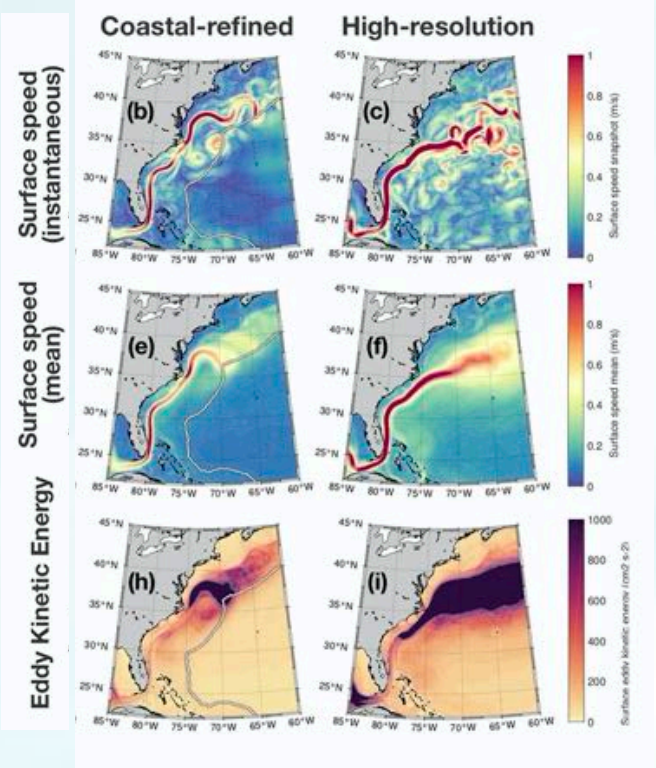
Eddy quality largely robust to mesh transitions

Hoch, K. E., Petersen, M. R., Brus, S. R., Engwirda, D., Roberts, A. F., Rosa, K. L., & Wolfram, P. J. (2020).
MPAS-Ocean Simulation Quality for Variable-Resolution North American Coastal Meshes. *Journal of Advances in Modeling Earth Systems*, *12*(3).

Role of regionally refined and high resolution



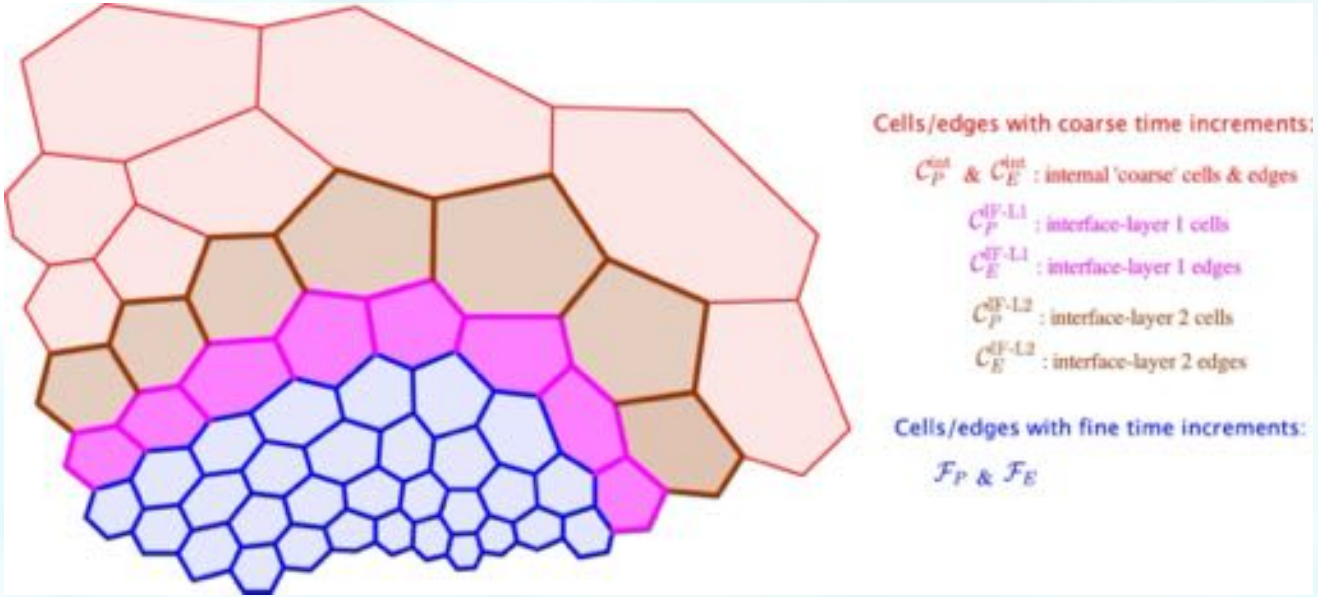
Upwelling similar to high-resolution



Mesoscale eddies resolved for mixing

Kevin L. Rosa, Mark R. Petersen, **Steven R. Brus**, Darren Engwirda, Kristin E. Hoch, **Mathew E. Maltrud**, Luke P. Van Roekel, **Phillip J. Wolfram**, Boundary current impacts of coastal refinement in the E3SM unstructured-mesh ocean model MPAS-Ocean, JAMES, in prep.

Spatially variable time stepping MPAS-O integration starting



Hoang, T., Leng, W., Ju, L., Wang, Z., & Pieper, K. (2019). Conservative explicit local time-stepping schemes for the shallow water equations. *Journal of Computational Physics*, *382*, 152-176.

Energy Exascale Earth System Model Science Questions

1. **Coastal flooding:**
   Regional sea level rise and inundation and inland flooding
   (water cycle and cryosphere system)

2. Land-river-ocean fluxes:
   Interactions between the human and natural systems via sediment/nutrients (biogeochemistry)

3. Coastal biogeochemistry:
   sediment transport and the terrestrial aquatic interface (biogeochemistry)

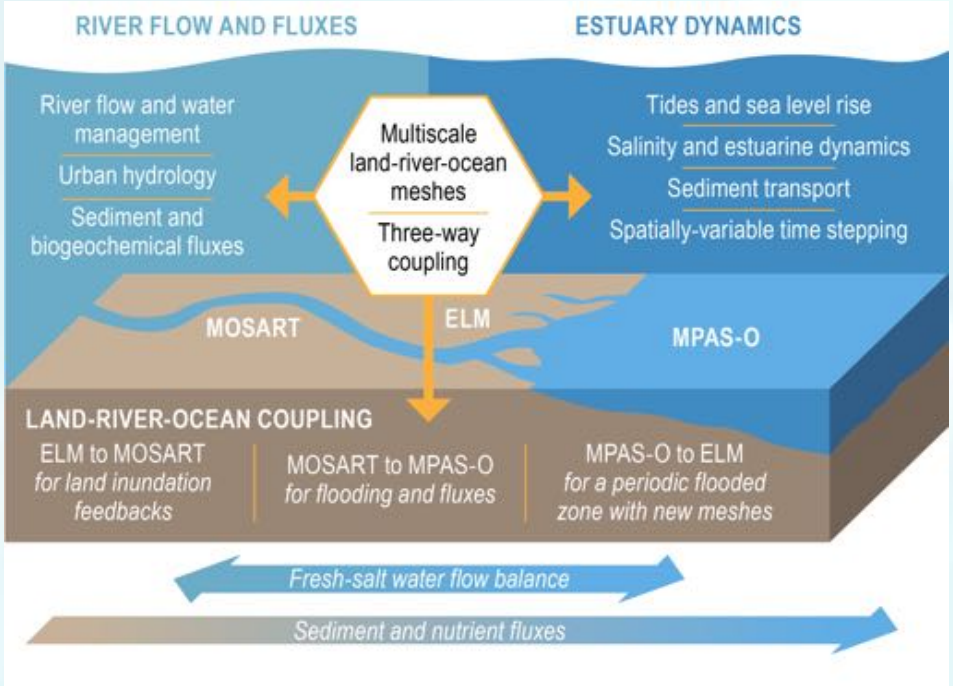
Questions	Medium-term (6-yr) experiments using v2	Long-term (10-yr) experiments using v3/v4
Water Cycle How does the hydrological cycle interact with the rest of the human-Earth system on local to global scales to determine water availability and water cycle extremes?	What are the relative impacts of global forcing versus regional effects of human activities on flood and drought risks in North America?	What are the moisture sources for precipitation over land? Do models converge with increasing resolution, and what controls this behavior? How will the moisture sources and precipitation over land change in the future?
Biogeochemistry How do the biogeochemical cycles interact with other Earth system components to influence energy-sector decisions?	What are the implications of different energy futures for the biogeochemical cycle through changes in land use land cover, water availability and extreme events?	What are the impacts of different energy and land use on the biogeochemical cycle and water availability? How might terrestrial-aquatic processes influence terrestrial and marine biogeochemistry?
Cryosphere Systems How do rapid changes in cryospheric systems evolve with the Earth system and contribute to sea level rise and increased coastal vulnerability?	How will the atmosphere, ocean and sea-ice systems mediate sources of sea-level rise from the Antarctic ice sheet over the next 30 years?	What processes and their model representations contribute to key uncertainties in projecting regional sea level rise? What are the implications to coastal inundation that result from interactions between sea level rise and extreme storms?

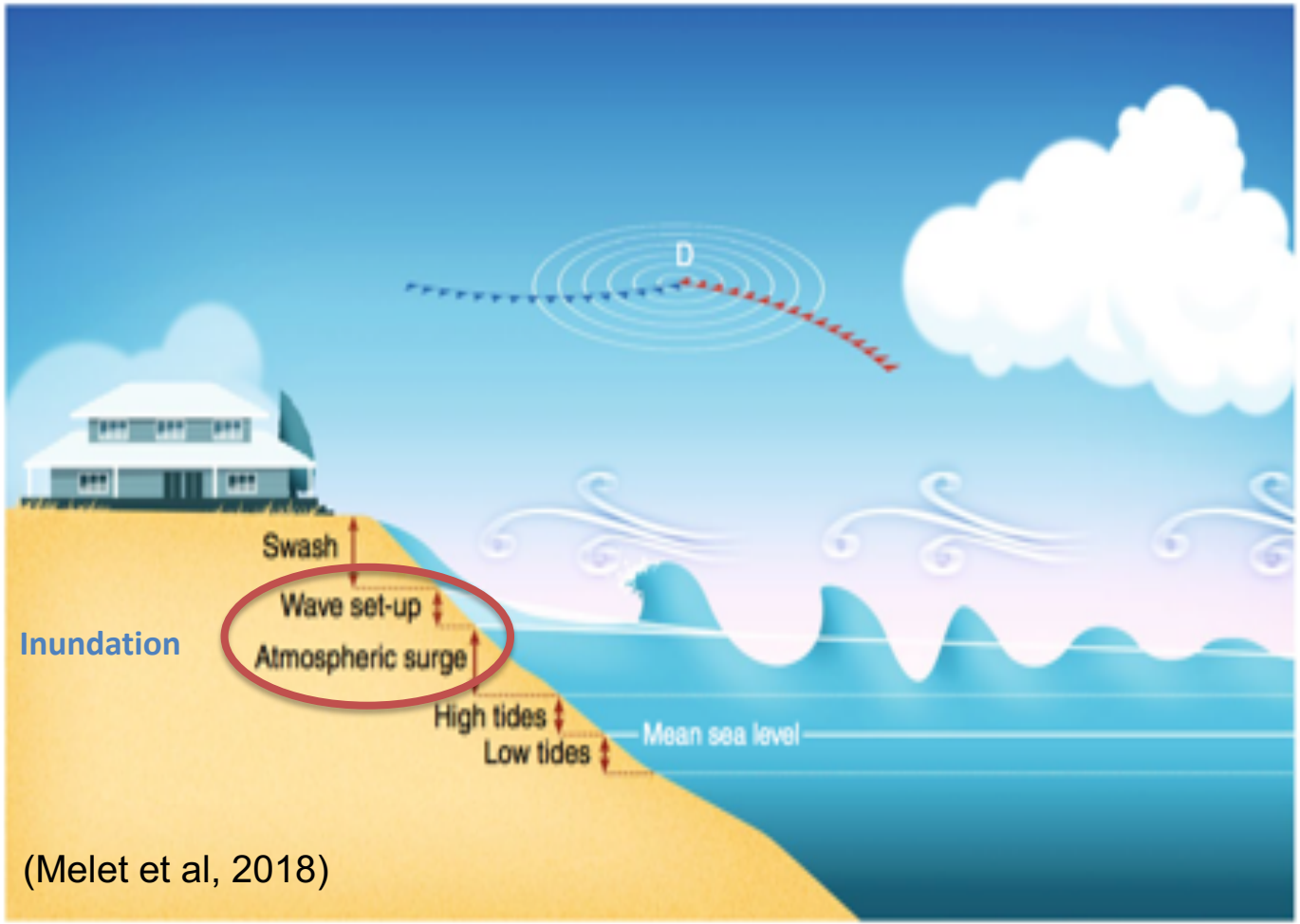
The New DOE Integrated Coastal Modeliing Earth System Model Development for E3SM

ESMD1. What is the sensitivity of coastal flooding to human and natural changes?

EMSD2. What are the interactions between processes and controls of coastal salinity, a key driver of coastal biogeochemistry?

ESMD3. What controls the coastal fate and transport of nutrients and sediment in terms of timing and spatial distribution?

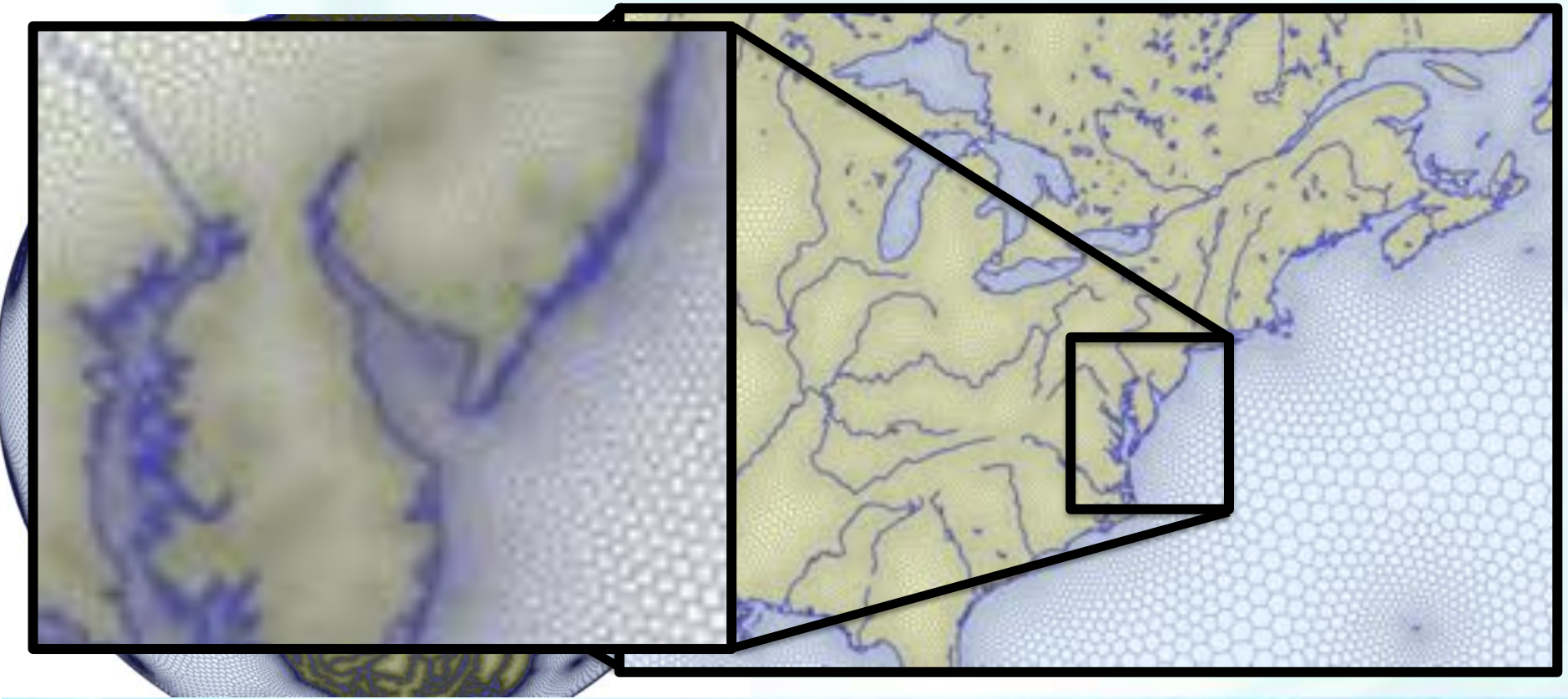




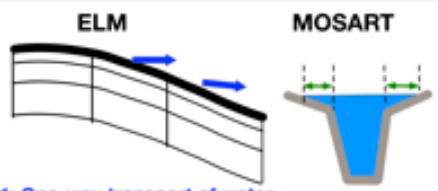
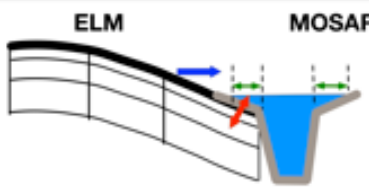
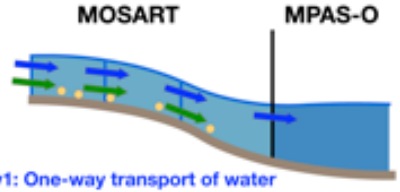
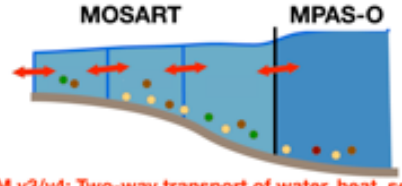
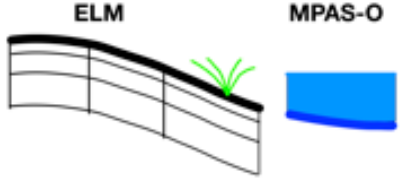
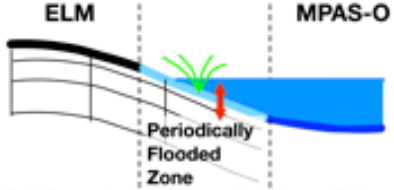
(Melet et al, 2018)

Global climate drivers

Unified land-river-ocean hexagonal meshes via prototype JIGSAW (D. Engwirda)

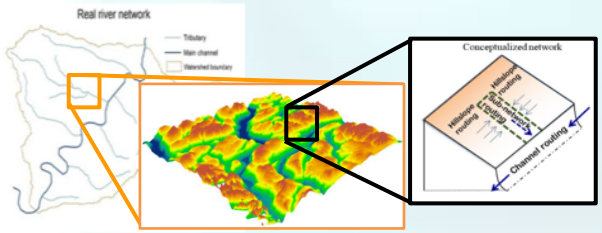


E3SM Coupling for the Land-River-Ocean

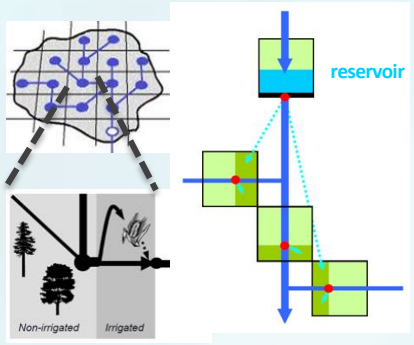
	Current and Ongoing	Proposed
Land ⇔ River	 E3SM v1: One-way transport of water E3SM v2*: Floodplain inundation estimated by MOSART	 E3SM v3/v4: Floodplain inundation will alter hydrologic, thermal, and ecological processes in ELM
River ⇔ Ocean	 E3SM v1: One-way transport of water E3SM v2*: Heat & sediment transport in MOSART	 E3SM v3/v4: Two-way transport of water, heat, sediment, and biogeochemistry
Land ⇔ Ocean	 E3SM v1 and v2*: Time invariant land/ocean fraction with no coupling between land and ocean components	 E3SM v3/v4: Dynamic land/ocean fraction with two-way exchange of water, heat, and biogeochemistry

Inland river flooding

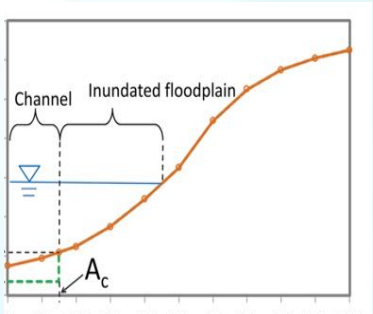
Coupling of land-river-ocean essential for compound events



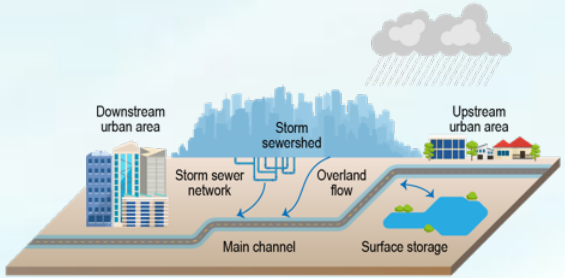
MOSART



MOSART – Water management



MOSART – Inundation



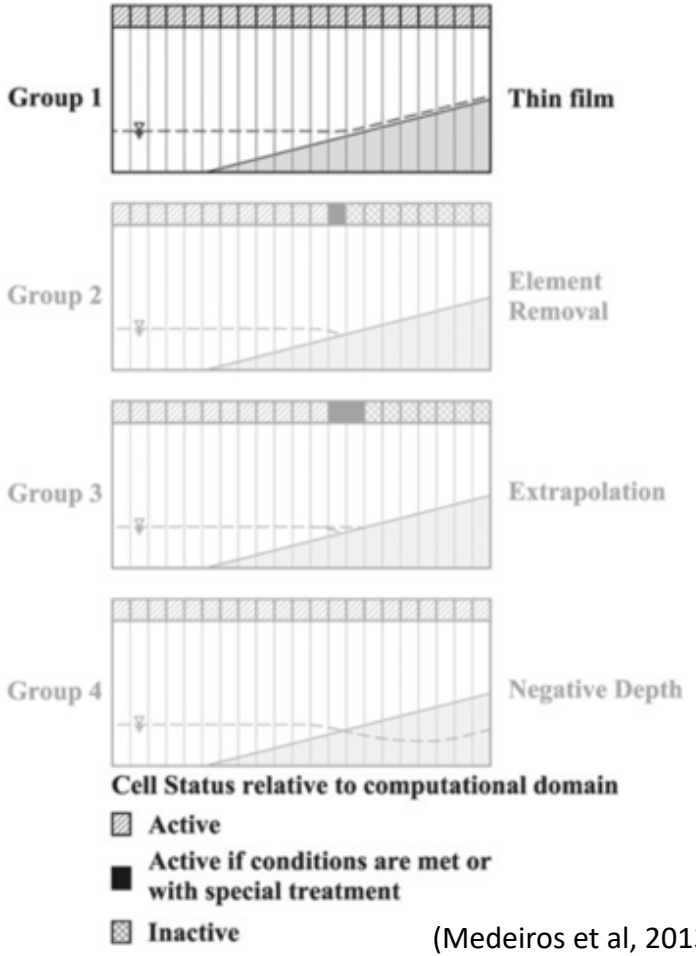
MOSART Urban

- Existing E3SM capability
  - Land runoff fluxes to river
  - River routing to ocean
  - Floodplain representation
  - Water management (e.g., dam operating rules)
  - Tri-grid configuration
  - MOSART-sediment
- New E3SM capability being developed in ICoM
  - Voronoi mesh
  - MOSART-Urban
  - MOSART-BGC
  - Backwater surge simulation

(Hong-Yi Li et al, 2013,2015; Luo et al., 2017; Voisin et al., 2013; Zhou et al., in revision)

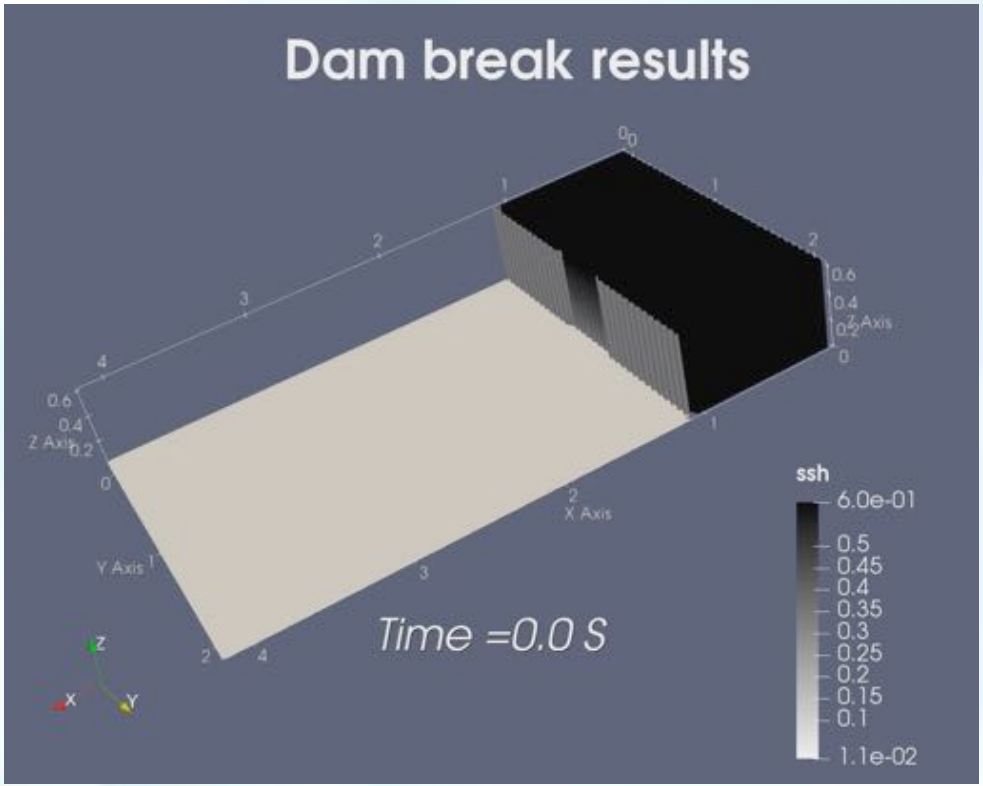
Coastal ocean flooding (MPAS-O wetting and drying)

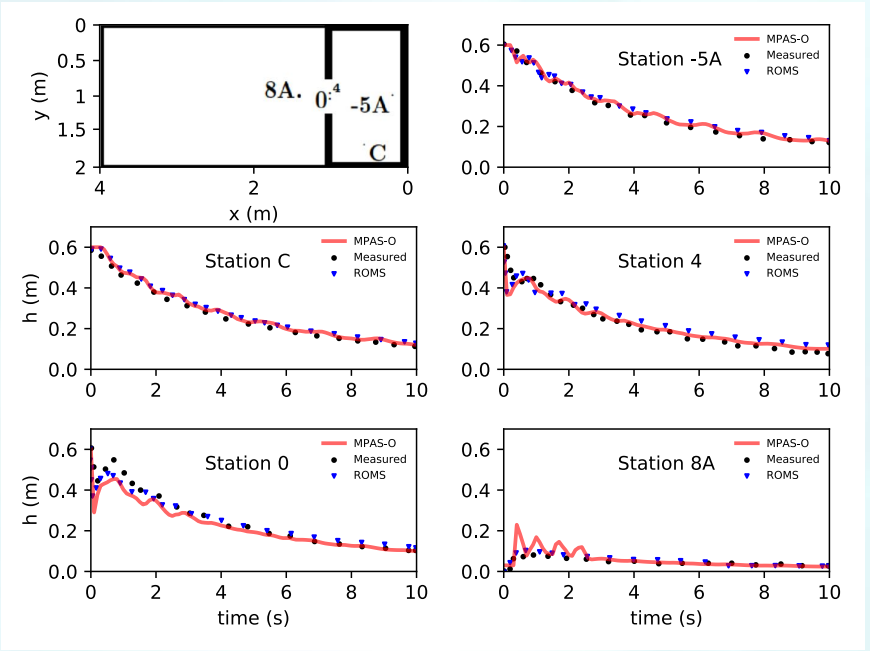
- Threshold velocity approach uses a thin-film approach, e.g., in POM, ROMS (Oey, 2005; Warner et al, 2013)
- Only outflowing divergence in cells has a damped velocity to implicitly prevent cell thickness from violating threshold (ensures flooding wave is accurate)
- Physical effect is a slowing of the gravity wave for drying cells, e.g., ebb of flood wave
- Evaluate using validation cases in Warner et al (2013)



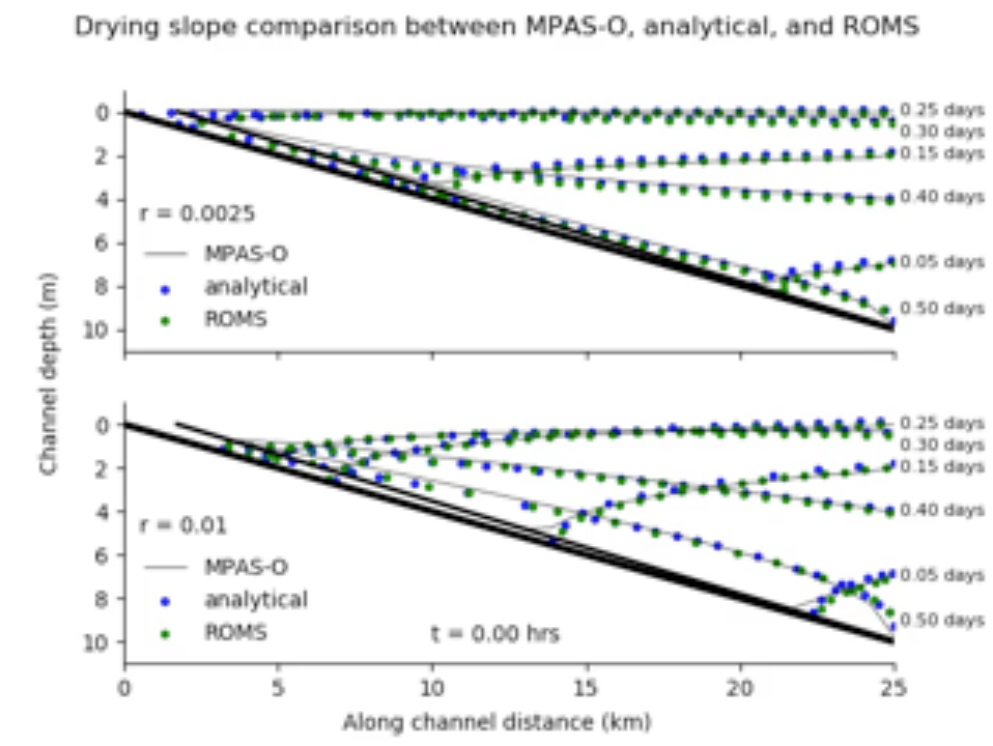
(Medeiros et al, 2013)

MPAS-O flooding validations from Warner et al (2013)

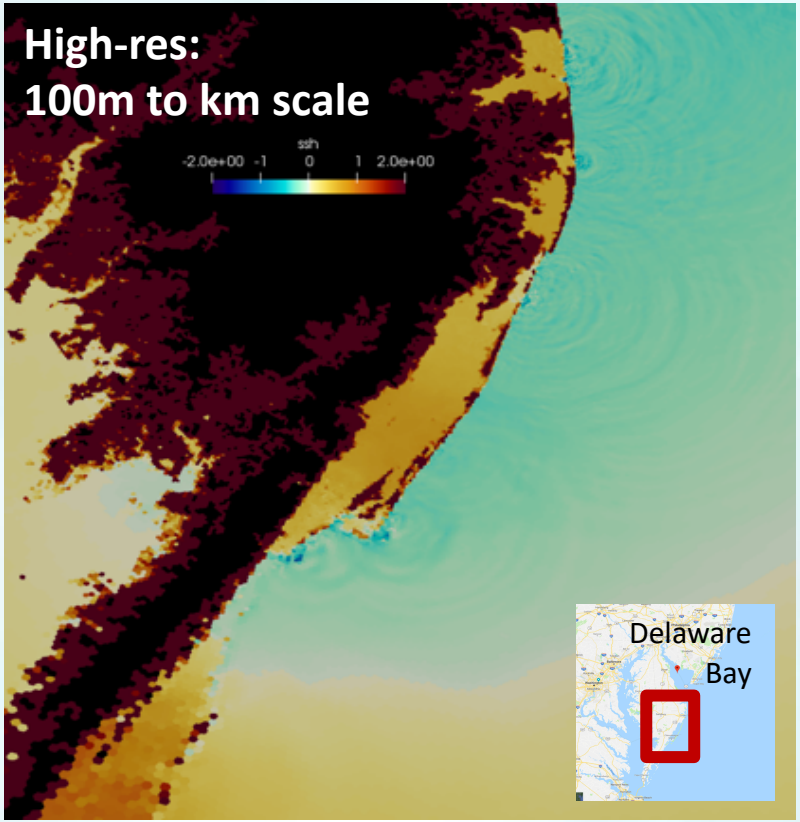




Inundation in MPAS-O



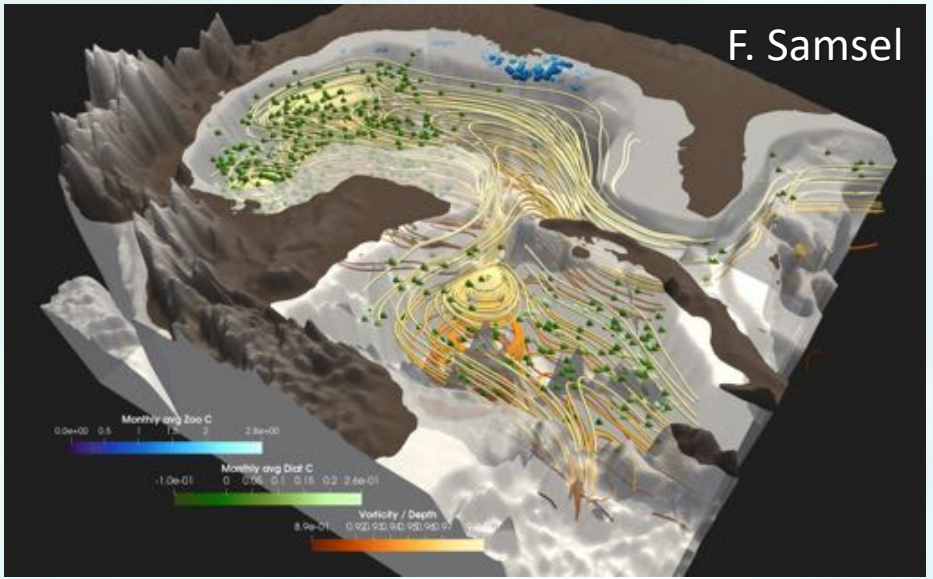
2D idealized shelf inundation with variable drag



Tidal flat flooding from idealized surge; Wolfram et al (in prep)

Incorporation of waves into E3SM (Steven Brus)

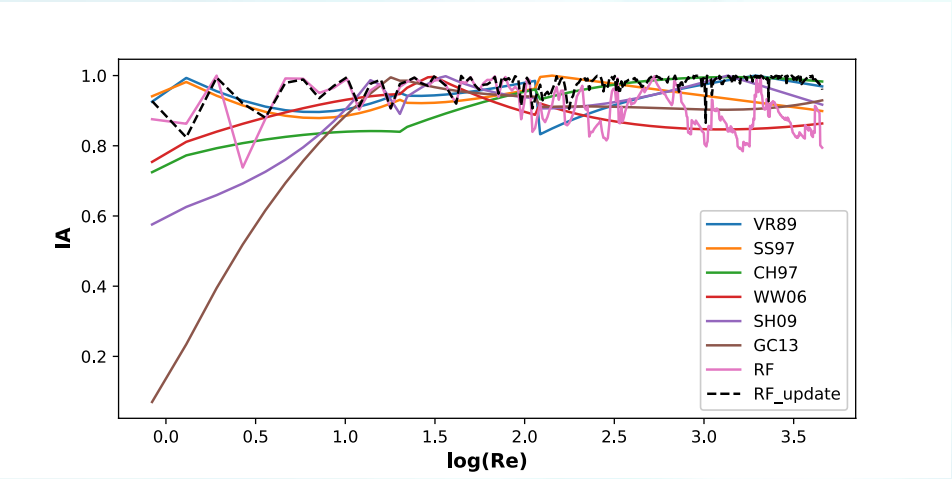
Sediment transport and biogeochemistry (multiscale processes requiring modeling)



Parameterizaiton and modeling of complex biogeochemistry and physical processes is inevitable

Development of a data-driven sediment falling velocity model (Cao et al, 2020)

- Sediment settling velocity is a key unknown in sediment transport codes and practice
- Developed a random forest model integrating a variety of observational datasets (RF) and leveraging sampling of common models (RF_update) that out predicts standard models
- Model illustrates the capability to improve parameterization of sediment settling velocity



$$IA_i = 1 - \frac{|w_{obs}^i - w_{pred}^i|}{w_{obs}^i}$$

Conclusions

- Coastal carbon cycle depends on coastal biogeochemistry
- Pure parameterized “box” approaches in Earth System Models insufficient
- Role of resolution essential in multiscale problems
  (but at cost of time stepping challenges)
- Coupling land-river-ocean necessary to understand coastal biogeochemistry and ecosystems
- Estuarine flows and fluxes essential precursors to coastal biogeochemistry
- Some processes require data-driven approaches (sediment transport)

Thank you!